Comment on "Experimental realization of Wheeler's delayed-choice GedankenExperiment"

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(Dated: Nov. 2, 2006)

A shortcoming in the authors' interpretation of this beautiful new experiment is pointed out and briefly discussed.

The new experimental realization [1] of Wheeler's delayed-choice thought experiment by Jacques, Wu, Grosshans, Treussart, Grangier, Aspect, and Roch (hereafter, "the experimenters") is a fantastic achievement. In the experiment, single photons are split at an initial beamsplitter, with the two "parts" then propagating along separate paths toward a detection area where a second beamsplitter can, at the last possible moment, either be inserted (causing the two "parts" to recombine and interfere) or removed (in which case one may simply observe which of the two paths was taken by the photon).

Of course, it is the aspect of delayed-choice which makes this so puzzling. With the second beam splitter in place, the observed interference can only be understood if something "split in half" and took both paths through the interferometer. But with the second beam splitter removed, the photon is (with high precision) observed in one or the other of the two beams exclusively, but never both.

As the experimenters explain it, "the striking feature is that the phenomenon of interference, interpreted as a wave following simultaneously two paths, is incompatible with our common sense representation of a particle which implies to follow one route or the other but not both." [1] But, because the "choice" (made by a Quantum Random Number Generator in this experimental realization) of whether the second beam splitter is to be inserted or removed is made *after* the photon has long since passed the initial beam splitter (at which it presumably would have to decide whether to split in half and take both paths, or select a single path) there appears to be a kind of non-local or backwards-in-time causation.

Actually, perhaps because he rejected as absurd any such non-local or reverse-temporal causation, Wheeler himself interpreted the significance of the thought experiment this way:

> "Then let the general lesson of this apparent time inversion be drawn: 'No phenomenon is a phenomenon until it is an observed phenomenon.' In other words, it is not a paradox that we choose what *shall* have happened after 'it has *already* happened.' It has not really happened, it is not a phenomenon, until it is an observed phenomenon." [2]

The experimenters are apparently less comfortable with this radically subjectivist and anti-realist philosophy, and simply claim that the experiment demonstrates a surprising sort of causality:

> "Our realization of Wheeler's delayed-choice GedankenExperiment demonstrates beyond any doubt that the behavior of the photon in the interferometer depends on the choice of the observable which is measured, even when that choice is made at a position and a time such that it is separated from the entrance of the photon in the interferometer by a space-like interval." [1]

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But does the experimenters' experiment really establish such non-local causation (or, for that mattter, Wheeler's subjectivism) *"beyond any doubt"*?

The answer is demonstrably negative. For a theory exists which can account for the observed results of Wheeler's delayed-choice experiment in a completely ordinary, local, common-sensical fashion. To see how this is possible, it is helpful to note an additional premise that Wheeler and the experimenters use in deducing from the observed results their respective conclusions. The premise is this: each "individual photon" is fundamentally, unanalyzably, ontologically *one thing*. It is only in the presence of this tacit premise that the claims

(i) something took exclusively one of the two available paths through the interferometer, and

(ii) something took simultaneously both paths through the interferometer

form together a logical contradiction which must be avoided by saying (naive appearances to the contrary notwithstanding) that, really, only one of (i) and (ii) is true. And it is precisely saying this which implies non-local causation since *which thing happened* is apparently influenced by our (later) choice to insert (or not) the beamsplitter.

But suppose, as postulated by the pilot-wave theory of de Broglie and Bohm, that each "individual photon" consists of two ontologically distinct aspects: a wave *and* a particle. [3] According to this theory, which is empirically equivalent to standard quantum theory, the photon *particle* obeys (i), i.e., it follows a definite trajectory and thus takes exclusively one or the other of the two possible paths through the interferometer. Meanwhile, the *wave*, in accordance with (ii), takes both paths. The trajectory of the particle is influenced by the wave in a way that explains exactly why the particle ends up where it ends up and with precisely the observed empirical frequencies under the various experimental conditions. And, crucially, the theory does this without in any way requiring us to posit a spooky backwards-in-time causation (or worse, dropping altogether the idea that something actually happened between the production and detection of the photon).

The theory of de Broglie and Bohm really exists, and really works. And it provides a stark counterexample to the claim that the results of Wheeler's delayed-choice experiment *require* "beyond any doubt that the [earlier] behavior of the photon in the interferometer depends on the [later] choice of the observable which is measured".

It is frustrating that this needs to be pointed out. The de Broglie - Bohm theory has existed for more than 50 years. Moreover, 25 years ago, J.S. Bell wrote an entire paper aimed at making this same point – that the pilot-wave theory provides an elegant alternative to the kinds of inferences made from Wheeler's delayed-choice experiment by physicists who are unduly in the grip of the orthodox quantum philosophy. [4]

One can do no better than simply quote Bell's penetrating summary of Wheeler's argument, and his explanation of how the de Broglie - Bohm theory eludes Wheeler's conclusion. First:

> The decision, to interpose the [beam splitter] or not, is made only *after* the pulse has passed the slits. As a result of this choice the particle *either* falls on one of the two counters, indicating passage through one of the two [arms of the interferometer], *or* contributes [to the building of an] interference pattern after many repititions. Sometimes the interference pattern is held to imply 'passage of the particle through both slits' – in some sense. Here it seems possible to *choose*, *later*, whether the particle, *earlier*, passed through one [arm] or two! Perhaps it is better not to think about it. 'No phenomenon is a phenomenon until it is an observed phenomenon."' [4]

Second: as Bell explains, in the de Broglie - Bohm theory

> "the wave always goes through both [arms] (as is the nature of waves) and the particle goes through only one (as is the nature of particles). But the particle is guided by the wave toward places where $|\psi|^2$ is large, and away from places where $|\psi|^2$ is small. And so if the [second beam splitter] is in position the particle contributes a spot to the interference pattern ... or if the plate is absent the particle proceeds to one of the counters. *In neither case is the earlier motion, of either particle or wave, affeted by the later insertion or noninsertion of the [beam splitter].*" (emphasis added) [4]

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There is a certain irony here associated with the fact that most physicists (at least, among those who have even heard of it) reject the de Broglie - Bohm theory because it is explicitly non-local. It's certainly correct that it is: the theory posits a mechanism whereby goings-on at the location of one particle, can affect the trajectory of another, distant (entangled) particle, sooner than signals propagating at the speed of light would permit. And this non-locality is crucial to the theory's ability to match the empirically correct predictions of standard quantum theory.

But the rejection of the pilot-wave theory on this basis is fallacious, for, as proved by Bell's Theorem, *any* theory which is in agreement with the experimental tests of Bell's Inequality must display a similar non-local causality.

Proponents of orthodox quantum theory, however, are often confused about this and think of *their* theory as perfectly local. But, simply put, it isn't: either one accepts (with Wheeler) an anti-realism which prevents the theory from saying anything dynamical at all (about, for example, photons), such that it simply doesn't say anything about the kinds of processes to which the terms "local" and "non-local" apply; or (like the experimenters) one must admit that the dynamics of the theory (in particular processes involving "measurement") are manifestly non-local. Either one stubbornly insists that the theory doesn't say *anything*, or one admits that what it says involves non-locality. The point is, in neither case can one claim that the theory provides a local description of the dynamics of photons (etc.).

The primary insight offered by the Wheeler delayed-choice experiment is that, while (as proved by Bell) any theory which agrees with *all* of the quantum mechanical predictions must be non-local, *some* theories display that troubling non-locality more often or more blatantly than others. Here is a situation which can be explained simply and locally by the de Broglie - Bohm theory, but whose explanation in terms of the orthodox quantum theory requires non-locality or worse. And so the irony is that those who reject the de Broglie - Bohm theory because it is non-local, and favor instead the standard version of quantum theory, unwittingly end up favoring something that is (in the sense just elaborated) *more non-local* than the theory they reject because it is non-local. Co-opting (for a purpose he wouldn't like) an infamous passage of N.D. Mermin: those for whom non-locality is anathema should (in response to Wheeler's experiment) reject orthodox quantum theory and flock to the pilot-wave picture! [5]

Of course, the real lesson here is just that anyone not conversant with the pilot-wave theory is severely hampered when it comes to interpreting the significance and meaning of fundamental experiments in physics. As Bell noted,

> "Even now the de Broglie - Bohm picture is generally ignored, and not taught to students. I think this is a great loss. For that picture exercises the mind in a very salutary way." [6]

And so one is naturally led to wonder, again following Bell:

> "Why is the pilot wave picture ignored in textbooks? Should it not be taught, not as the only way, but as an antidote to the prevailing complacency? To show that vagueness, subjectivity, and indeterminism are not forced on us by experimental facts, but by deliberate theoretical choice?" [7]

Tragically, decades later, physicists (who apparently still remain ignorant of the important lessons of de Broglie and Bohm) are still making the latter choice (apparently without even realizing they are making a choice). One can only hope that the more reasonable choice – of acknowledging the real existence of the pilot wave theory and learning the important lessons it has to teach – will be not much longer delayed.

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[1] V. Jacques, E. Wu, F. Grosshans, F. Treussart, P. Grangier, A. Aspect, and J.-F. Roch, "Experimental realization of Wheeler's delayed-choice GedankenExperiment" quant-ph/0610241

[2] J.A. Wheeler, "The 'Past' and the 'Delayed-Choice Double-Slit Experiment", pages 9 - 48 in *Mathematical Foundations of Quantum Theory*, (A.R. Marlow, editor), Academic Press, 1978.

[3] For an introduction to this theory, one can do no better than S. Goldstein's article on "Bohmian Mechanics" in *The Stanford Encyclopedia of Philosophy (Summer 2006 edition)*, Edward N. Zalta (ed.), http://plato.stanford.edu/archives/sum2006/entries/qm-bohm/.

[4] J.S. Bell, "de Broglie - Bohm, delayed-choice double-slit experiment, and density matrix", *International Journal of Quantum Chemistry*: Quantum Chemistry Symposium, **14** (1980) 155-9.

[5] N. David Mermin, "Hidden Variables and the Two Theorems of John Bell", *Rev. Mod. Phys.*, **65** (1992), pp. 803-815. See also T. Norsen, "EPR and Bell Locality", *AIP Conference Proceedings, Quantum Mechanics: Are There Quantum Jumps?* and *On the Present Status of Quantum Mechanics*, Vol. 844, pp. 281-293, June 2006. (quant-ph/0408105)

[6] J.S. Bell, "Speakable and unspeakable in quantum mechanics". Introductory remarks at Naples-Amalfi meeting, May 7, 1984. Reprinted in *Speakable and Unspeakable in Quantum Mechanics*, Second Edition, Cambridge University Press, 2004.

[7] J.S. Bell, "On the impossible pilot wave", *Foundations of Physics*, **12** (1982) pp 989-99.